The mechanics of cohesive powders.

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SUMMARY

When stored in silo's, powdered materials are compressed due to gravitational forces. For cohesive materials such a compression generally leads to an increase of the mechanical strength of the powder mass. It may even occur that the strength of the material reaches values large enough to form stable obstructions that cause serious problems during the discharge of the silo. Being part of a research project, started at the University of Groningen in 1975 in order to develop a device to promote the flow of cohesive powders from silo's, the work described in this thesis mainly intends to increase the insight into this phenomenon.
The approach is essentially different from current experimental methods in the field of powder mechanics, in so far as it is based on the use of a triaxial cell to measure the mechanical properties of cohesive powders. The major advantage of this apparatus is a well defined state of stress, and results of experiments accordingly can be used for a well defined fundamental interpretation.
This thesis further aims to present various geometrical forms for the eventual design of a flow promoting device based on simultaneous vibration and aeration of cohesive powders.

The study of the (flow) behaviour of cohesive powders in silo's has two main aspects. These are on the one hand a well defined characterisation of the mechanical properties of such materials, and on the other hand a reliable estimation of the stresses that occur in a powder mass inside a silo. This thesis contains five studies that are devoted to these two aspects.

The mechanical properties of cohesive powdered materials have to be determined after various degrees of compression (consolidation) of the material. This compression has been studied first in order to understand why during compression certain materials show discontinuities that appear as crackling. From this study it

appeared that powdered materials crackle if the stacking is highly compressible and if at the same time the powder particles are elastic and rather soft. As a result of this discontinuous behaviour the packing density of compacts of this kind of materials may vary at random between certain limits, imposing unavoidable limits upon the reproducibility of experiments with these compacts.

The most characteristic mechanical property of cohesive powdered materials certainly is the so-called unconfined yield strength, which is the strength of a compact under a unidirectional load. From the second study described in this thesis, the unconfined yield strength of powder compacts appeared to depend strongly on the magnitude of the consolidation stresses. It also appeared to depend significantly on the period of time during which the consolidation load has been applied. These two effects could be fitted very well empirically by one single power law equation. It further appeared that the strength of powder compacts can depend on the temperature of the material. For some potato starch samples for instance, a 50% increase of the strength was observed for an increase of the temperature from $10^{o}C$ to $30^{o}C$. These phenomena are for a major part attributable to the deformation of particle to particle contact points under the influence of the force with which they are pressed together.

Since in practical situations powder masses are generally consolidated anisotropically, the third study described in this thesis was devoted to the influence of the degree of stress anisotropy during consolidation on the mechanical properties of a compact. The unconfined yield strength of various materials was found to increase linearly with this parameter, with a rate of increase that is unexpectedly large. The theoretical model of Molerus that claims to describe this phenomenon, had to be rejected because it could in no way be brought into agreement with the experimental results.

The stress distribution in powder masses that are stored in silo's, has been the subject of many studies already. Part of the work reported in this thesis is meant to be a further contribution to these studies, in so far that the validity of certain theoretical models is investigated.

For silo's with vertical walls there exist several theories to predict the stress distribution that start from the assumption that the powder mass is in the so-called critical state of stress. This state of stress is an equilibrium situation where small shear deformations do not lead to changes in the packing density. Using the triaxial cell, that can be operated to simulate a silo with frictionless vertical walls, it could be proved that powder masses in such silo's, however, do not attain this critical state of stress. When the silo walls are not frictionless this does not seem to be the case either.

For silo's with a conical outlet section, Jenike has developed a theory to describe the stress state in this conical part, which he expanded to a prediction whether stable powder arches can occur. The validity of this approach had not yet been verified, because the current experimental methods for obtaining data on the mechanical properties of cohesive materials do not allow measurements at the very low degrees of consolidation as occur in the conical part of a silo. In this thesis a method is described to obtain these data. Using these data, the formation of powder arches in a small scale wedge-shaped hopper could indeed be predicted fairly well using the theory of Jenike.

The flow promoting device that recently was developed at the University of Groningen, consists of a flexibly mounted vibrated bottom that simultaneously serves as an aeration bottom. This simultaneous action of vibration and aeration gives cohesive materials a fluid-like character that enables a regular and controllable flow. Since industry has already shown great interest in the use of such a device, the last study described in this thesis has been devoted to the geometrical lay-out of this system, especially with a view to upscaling. From experiments with various designs it appeared that there exists a fair degree of flexibility. For large scale operations a vibrated aeration bottom combined with a stationary (aerated) cone, for instance, appeared to be a promising system.